

The Gran Sasso muon puzzle

Enrique Fernandez-Martinez and Rakhi Mahbubani
Theory Division, CERN, 1211 Geneva 23, Switzerland.

We carry out a time-series analysis of the combined data from three experiments measuring the cosmic muon flux at the Gran Sasso laboratory, at a depth of 3800 m.w.e. These data, taken by the MACRO, LVD and Borexino experiments, span a period of over 20 years, and correspond to muons with a threshold energy, at sea level, of around 1.3 TeV. We compare the best-fit period and phase of the full muon data set with the combined DAMA/NaI and DAMA/LIBRA data, which spans the same time period, as a test of the hypothesis that the cosmic ray muon flux is responsible for the annual modulation detected by DAMA. We find in the muon data a large-amplitude fluctuation with a period of around one year, and a phase that is incompatible with that of the DAMA modulation at 5.2σ . Aside from this annual variation, the muon data also contains a further significant modulation with a period between 10 and 11 years and a power well above the 99.9% C.L threshold for noise, whose phase corresponds well with the solar cycle: a surprising observation for such high energy muons. We do not see this same period in the stratospheric temperature data.

I. INTRODUCTION

There has been a recent resurgence of interest in alternative explanations for the annual modulation signal detected by DAMA/LIBRA, the dark matter direct detection experiment located at the Gran Sasso National Laboratory (LNGS), Italy. The DAMA/LIBRA data [1, 2], together with those of its previous incarnation, DAMA/NaI [3, 4], show a clear modulation (at 8.9σ) that is consistent with the dark matter hypothesis both in period and phase. However, there has been widespread skepticism for the interpretation of this signal as evidence for dark matter direct detection. Alternative interpretations have been proposed: one of these is background induced by cosmic muons, the flux of which also modulates annually with a peak in the summer, in the northern hemisphere, due to temperature fluctuations in the stratosphere. A (convoluted) mechanism by which the modulating cosmic muons might give rise to a signal in the DAMA detector, involving intermediate spallation neutrons, was proposed in [5]. This hypothesis has not been independently tested, and recently several arguments against it were put forward by DAMA [6]. Here we will examine more closely one of these arguments, namely the compatibility between the period and phase of the DAMA and muon annual modulations.

Independent assessments of the compatibility of the DAMA signal with the cosmic muon flux, the latter taken from the LVD experiment [7] at LNGS, whose period of data taking coincided with the first 5 runs of DAMA/LIBRA, were carried out in [8] and [9], with contradictory conclusions. However, LVD is not the only experiment measuring the cosmic muon flux at the LNGS site; including the data from MACRO [10] and Borexino [11] gives a 20-year span of muon modulation data, fully encompassing the time-span of both DAMA/NaI and DAMA/LIBRA. We analyse for the first time the combined data set and find an annual modulation whose phase is rather incompatible with DAMA's. Intriguingly for such high energy muons, we also see significant power

at a period of just over 10 years, with a phase that represents a close anticorrelation with the solar cycle. We present our results in Sec. II and discuss their implications in Sec. III.

II. RESULTS

A. Muons and DAMA

We begin by subtracting, from the data of LVD and Borexino, the average muon flux reported over the course of the experiment, in order to normalize them to the same baseline (MACRO already presented its data in this form). We then carry out a simple chi-squared fit of the combined data to a cosine of unknown amplitude, period and phase, marginalising over an added constant for each individual experiment, to allow for the effect of systematic flux mis-measurements, as well as their different sensitivities for through-going muons¹. The best-fit cosine has a period of 365.9 ± 0.2 (solar) days and a phase of 177.4 ± 2.2 days (with respect to January 1st 1991). While these numbers are generally in good agreement with the fits carried out by the individual experiments, the goodness of fit, quantified by a value of chi-squared per degree of freedom of 7587/4244, is rather poor.² This is unsurprising: while we expect the annual modulation of muons, which is directly related to temperature fluctuations in the stratosphere, to be periodic, this periodicity

¹ Neither the period nor phase of the leading behaviour change significantly on inclusion of these constants.

² Our assessment of the best fit parameters and uncertainties for each individual experiment are in good agreement with the values quoted by the collaborations themselves, with the exception of LVD's uncertainties in the period and phase [7], which are an order of magnitude larger than ours, at fifteen days. Such a large shift, particularly in the period, would certainly be visible by eye over an 8-year time-span, and we find no evidence for this in the data.

is unlikely to be sinusoidal. Similarly we carry out a chi-squared fit to DAMA/NaI and DAMA/LIBRA data and find a period and phase in good agreement with those quoted by the collaboration themselves. We plot confidence limit contours for the muon and DAMA data sets in the 2D period-phase plane in Fig.2 below. As pointed out in [9], because the periodicity is allowed to vary, the size and shape of the contours are affected by the choice of time origin. We have verified, however, that the relative (dis-)agreement between the two sets of data in chi-squared units is independent of the choice of the origin, as it should be, and is also relatively stable over the entire timespan of the experiments. We use the parameter goodness of fit [12], to quantify the level of compatibility between DAMA and the muon data when measuring the period and phase. The p-value for the two data sets measuring the same parameters is 2.2×10^{-7} , which corresponds to a 5.2σ tension between them. This supports the conclusion in Chang et. al. [9] of no strong correlation between the annual oscillation of cosmic muons and the DAMA signal, with two caveats. The first is that the mechanism by which the muons generate a signal in the DAMA detector does not significantly smear the phase of the modulation³. The second is that we test for a correlation with the assumption of sinusoidal behaviour for the cosmic muon modulation, which is a rather poor one, as can be seen from the value of the chi-squared per degree of freedom. Indeed, when fixing the period to one year and extracting the phase for each independent year of the two datasets to test for the stability over time of the results, we found that the yearly DAMA results are always compatible within their uncertainties with the average value over the length of the experiment. On the other hand, the cosmic muon data shows a larger yearly dispersion evidencing again the pooriness of the sinusoidal approximation for the muon data. However, we expect that a more sophisticated statistical analysis of the data sets, that does not rely on this assumption, will yield a similar conclusion.⁴

B. Muons and the solar cycle

Even more interesting perhaps are the results from our systematic tests for the existence of a subleading, longer-term variation in the muon flux, such as that noticed by Blum [8] in the LVD data. We fit the combined muon data to a sum of two cosines, with unrelated and

unknown amplitudes, periods and phases, marginalising over a constant shift parameter for each experiment as before (see Fig. 1 for best-fit curve). We find the leading annual modulation almost unchanged, but the chi-squared for the fit improves by over 250 units on addition of the second cosine, with an amplitude of $0.40 \pm 0.03\%$; a period of 10.7 ± 0.3 years and a phase of 1880 ± 50 days (corresponding to a first maximum in March 1996). As a quantitative measure of the significance of the subleading periodicity in muon data, we plot a Lomb-Scargle periodogram [13–15], for the full cosmic muon data set. Like an inverse Fourier transform, this prescription separates a periodic signal into its harmonic constituents, but is tailored to work even for unevenly-spaced data. It has well-understood statistical properties, for example it is known to yield an exponentially-falling power when the input is random Gaussian noise. Given the large disparity between the size of the error bars in the data from the different experiments, however, we find it necessary to weight the data points by their individual error bars, as proposed in [16], thus making the information in the periodogram more analogous to that obtainable using a chi-squared fit [14]. We use an oversampled set of frequencies based on the natural frequencies of the data set in order to obtain a good resolution on the resulting periodogram, and estimate the threshold power at which noise can be excluded at the 99.9% C.L. using the prescription provided in [17]. We generate 10,000 samples of random Gaussian noise, with identical spacing to the muon data, and with the same variance and error bars. We then compute the weighted Lomb-Scargle periodogram for each sample, for our standard set of oversampled natural frequencies, and use the distribution of the power of the highest peak in each plot as a measure of the “false-alarm” probability. Our results can be seen in Fig. 3(a). The dominant feature is a peak at 1 year (truncated due to the range of the plot). There seem to be many subdominant peaks, including one around 10 years, although it is unclear how to interpret them, since it is only possible to come to a statistically rigorous conclusion about the dominant peak in a given L-S periodogram. We therefore repeat the above procedure after filtering out the annual modulation, by subtracting from the data a cosine with the best-fit annual parameters. The resulting periodogram can be seen in Fig. 3(b), with the limit for exclusion of noise at the 99.9% confidence level (now given the presence of an annual modulation with the pre-defined properties) shown as a dotted line. In the subtracted periodogram one can clearly see in the cosmic muon flux a harmonic component with a period of 10.4 ± 0.3 years⁵. Many of the small-period spikes present in the periodogram for the full data set have vanished af-

³ A simple smearing by a Poisson distribution to account for the stochastic nature of this process, proposed in [8], is insufficient to overcome the tension between the two data sets, for smearing by any distribution of reasonable width.

⁴ Note that even taking LVDs quoted uncertainties at face value does not significantly change the degree of discrepancy between phases of the cosmic muon flux and DAMA data since MACRO and Borexino data are enough to provide a 4.7σ tension.

⁵ This is in fact the same period that is obtained using a chi-squared fit, in the absence of the constant term, added to account for systematics.

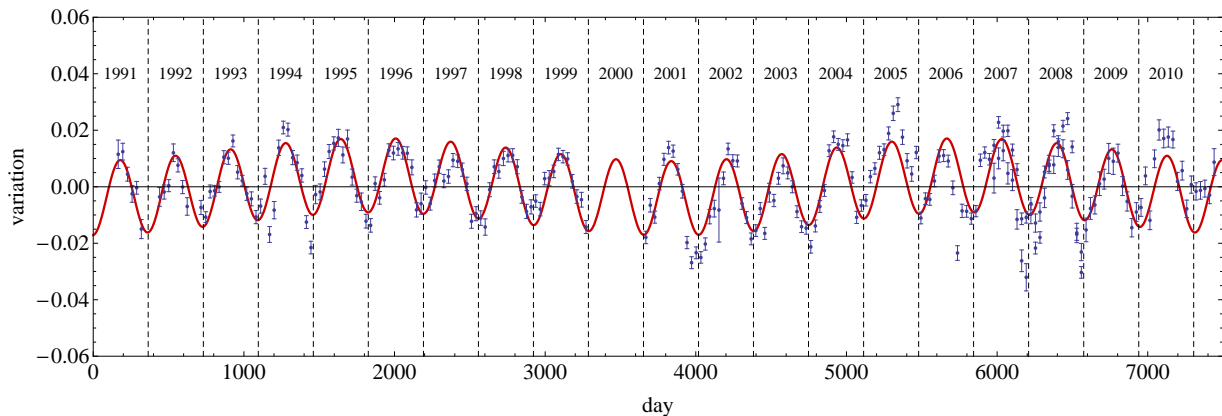


FIG. 1: Combined cosmic muon data from MACRO, LVD and Borexino, with monthly binning for clarity, after subtraction of the mean measured flux at each experiment, as well as of an additional constant, determined for each individual experiment by the chi-squared fit. This constant, which accounts for systematic differences in the experiments' sensitivities to cosmic muons, has a negligible effect on the best fit period, phase and amplitude for the annual modulation. The best fit to the sum of two independent cosines yields the solid line in the figure (periods, phases and amplitudes detailed in the text).

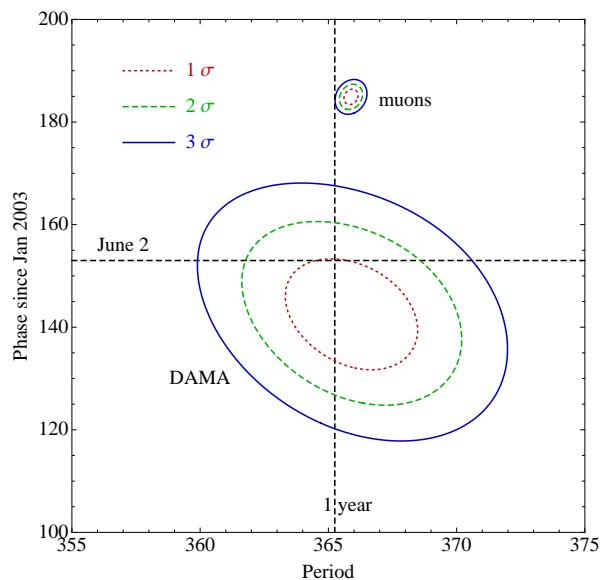


FIG. 2: Confidence-limit contours for period and phase of best-fit cosine for cosmic muon flux from MACRO, LVD and Borexino, and DAMA data. The straight black-dashed lines delineate the expected period and phase for a dark matter signal. See text for note concerning changes in time origin.

ter harmonic filtering of the annual modulation, leading us to conclude that they were aliasing peaks, or some other artifact of the irregular data spacing or sampling frequencies used. The subleading periodicity in the muon data, as seen in both the chi-squared fit and the L-S periodogram, displays a strong correlation with the solar cycle. We also plot for comparison the weighted Lomb-Scargle periodogram for the monthly-averaged sunspot data in the same period, taken from [18], and originally derived from data by the Solar Influences Data Analysis Center in Belgium in Fig. 3(c). We see a dominant

peak corresponding to a period of 12.6 ± 0.1 years, and what looks like higher harmonics of this fundamental frequency. Caution must be exercised in interpreting the fitted periods and uncertainties presented in this subsection: the solar cycle is known to have a rather variable period, making the cosine fit an inadequate description of the data, as reflected in the large chi-squared values. This does not, however, preclude the use of these fit values to compare two data sets under the hypothesis of a correlation between them.

In order to test for a possible correlation between the secondary modulation in the Gran Sasso cosmic muon data and the sunspot data, we again make use of the parameter goodness of fit, with parameters extracted from a chi-squared fit of both the muon and sunspot data to cosine functions with a relative phase of π . While the fitted phases are in agreement, we find there is a 4.7σ tension between the fitted periods, which is not very encouraging. Notice, however, that in the fits, the sunspot data are weighted by their variance, which in the limit of low statistics is strongly dependent on their absolute values, making data taken during minimums of solar activity dominate the fit. Because of this, the fitted period is driven to large values by the unusually long and deep solar minimum around 2008. By contrast, the corresponding muon data was taken mostly by Borexino, which has comparatively large error bars. Thus, muon data give more weight to earlier parts of the solar cycle, which fit better with smaller periods. Indeed, redoing the fit after rescaling the sunspot error bars such that the relative size of the error bars (and hence their weights) are the same as in the muon data reduces the tension between the two data sets to 2.1σ . Furthermore, as mentioned above, a sinusoid with a constant period is a particularly bad model for sunspot activity (522/242 for the chi-squared per dof), which is cyclical rather than periodic. Performing a fit to the sunspot data using a cosine with a period

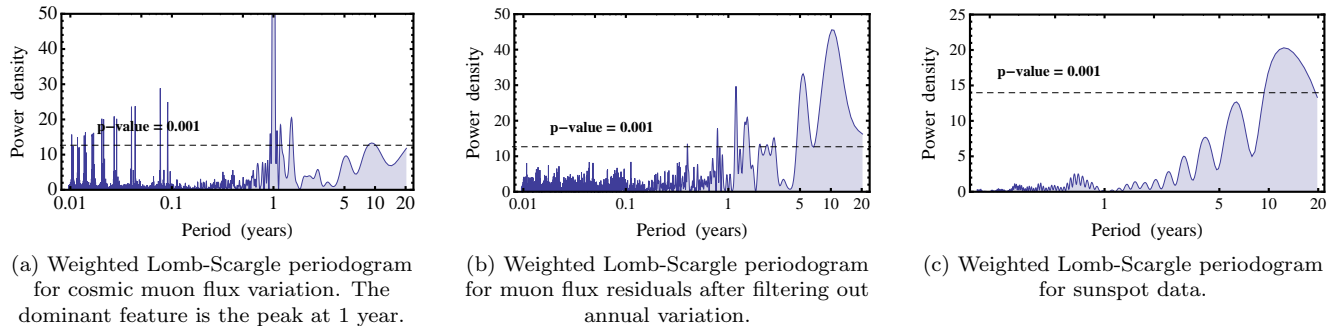


FIG. 3: Weighted Lomb-Scargle data showing subleading 10.4-year period in cosmic muon flux variation, and correlation with sunspot data, for the period January 1991 to April 2011.

that varies linearly in time instead results in a very accurate description of solar data over the two cycles in question, with an improvement in the chi-squared per dof (to 249/241), and a fitted “period” which varies from 8 to 13 years. With this phenomenologically-motivated fitting function, we find that the discrepancy between both data sets reduces to less than 1σ , seemingly implying a close correlation between them.⁶ This correlation is rather puzzling given that the cosmic muon flux is being measured at 3800 m.w.e. below the earth’s surface, which corresponds to a threshold muon energy of 1.3 TeV at sea level.

The variation of the cosmic ray flux with the solar cycle is a known phenomenon, one that is now understood to be due to larger magnetic fields, and increased turbulence from the solar wind at a solar maximum, deflecting low energy cosmic, thus preventing them from reaching the earth. According to the common lore [19, 20], however, one should not expect to see this effect persist at energies larger than tens of GeV for the primary cosmic, and hence also for its decay products. The persistence of this effect to muons of energies larger than $\mathcal{O}(\text{TeV})$ is likely not due to long-term changes in the stratospheric temperature, since we do not see the corresponding period in the effective temperature periodogram (computed as detailed in [21], using atmospheric temperature records taken at the nearby Pratica di Mare station, from the Integrated Global Radiosonde Archive [22]). There is possibly a more subtle mechanism at work; coming up with a suitable candidate, however, will require a detailed analysis of the interplay between cosmic ray propagation and atmospheric effects, and is beyond the scope of this paper.

III. DISCUSSION

We combined the measurements of the cosmic muon flux from three Gran Sasso-based experiments, MACRO, LVD, and Borexino, and analysed the resulting 20 years of data in the light of claims that cosmic muons might somehow be responsible for the 8.9σ annual modulation measured at DAMA. In fitting the muon and DAMA data to a sinusoidal variation of unknown amplitude, period and phase, we find the two data sets have periods that are compatible, but their phases are in conflict at 5.2σ .

Without a working model by which muons might fake a signal in the DAMA detector, a possible role for cosmic muons in DAMA’s annual modulation cannot be ruled out by these arguments alone. However, it seems challenging to find a mechanism that can bridge a phase discrepancy of 5.2σ between the two datasets. Alternatively, DAMA might be measuring the resultant effect of two annual modulations with slightly different phases, one of which results from contamination by cosmic muons.

We subsequently separated the muon data into its harmonic components using a Lomb-Scargle periodogram. We found in addition to the annual modulation, a subdominant modulation of period just over 10 years with a power well above the 99.9% C.L. for noise, and a phase that is anticorrelated with the solar cycle. This result was confirmed using a chi-squared fit.

A correlation between such high energy muons and the solar cycle goes against the common lore: one might expect energetic cosmic that produce these muons to be unaffected by the presence of the larger solar magnetic fields and stronger solar winds of a solar maximum. This puzzling observation is unlikely to be due to contamination by cosmic neutrinos, whose flux at the depth of the Gran Sasso lab (3800 m.w.e.) would be subdominant to the muon flux, and too small to account for this effect [23]. Moreover, we found no evidence for such long-term modulation in the effective stratospheric temperature close to Gran Sasso. The reason for the persistence of this effect to high-energy muons possibly stems from some complex interplay of atmospheric effects and secondary cosmic production, but the detailed modelling of

⁶ In contrast, we were unable to find an alternative function that provided a better fit to the annual modulation of muons.

these effects is beyond the scope of this work.

Independent tests of a potential correlation between high energy cosmic rays and the solar cycle should already be possible at a number of long-running experiments, including underground detectors such as Super-Kamiokande, and terrestrial experiments such as AGASA or HiRes. Additional facilities exist that are currently taking cosmic ray data, like IceCube and MINOS for muons, or Extensive Air Shower experiments such as the

Tibet Air Shower Array and Argo-YBJ. In a number of years, these will have collected enough data to probe the relevant time scales, allowing us to explore the dependence of any modulation with the depth, latitude and longitude at which the observations were recorded, as well as its energy and flavour-dependence. Finally, satellite experiments can directly probe the primary cosmic rays, yielding crucial information for our ultimate understanding of this effect.

-
- [1] R. Bernabei, P. Belli, F. Cappella, R. Cerulli, F. Montecchia, et al., Riv.Nuovo Cim. **26N1**, 1 (2003), astro-ph/0307403.
 - [2] R. Bernabei, P. Belli, F. Cappella, R. Cerulli, F. Montecchia, et al., Int.J.Mod.Phys. **D13**, 2127 (2004), astro-ph/0501412.
 - [3] R. Bernabei et al. (DAMA), Eur. Phys. J. **C56**, 333 (2008), 0804.2741.
 - [4] R. Bernabei et al. (DAMA), Eur. Phys. J. **C67**, 39 (2010), 1002.1028.
 - [5] J. P. Ralston (2010), 1006.5255.
 - [6] R. Bernabei, P. Belli, F. Cappella, V. Caracciolo, R. Cerulli, et al. (2012), 1202.4179.
 - [7] M. Selvi et al. (LVD Collaboration), Proceedings of the 31st International Cosmic Ray Conference (2009).
 - [8] K. Blum (2011), 1110.0857.
 - [9] S. Chang, J. Pradler, and I. Yavin (2011), 1111.4222.
 - [10] A. Moussa (2009), 0911.4873.
 - [11] G. Bellini (Borexino Collaboration) (2012), 1202.6403.
 - [12] M. Maltoni and T. Schwetz, Phys.Rev. **D68**, 033020 (2003), hep-ph/0304176.
 - [13] N. Lomb, Astrophys.Space Sci. **39**, 447 (1976).
 - [14] J. Scargle, Astrophys.J. **263**, 835 (1982).
 - [15] J. Horne and S. Baliunas, Astrophys.J. **302**, 757 (1986).
 - [16] P. Sturrock, Phys.Rev. **D72**, 113004 (2005), hep-ph/0408017.
 - [17] F. Frescura, C. Engelbrecht, and B. Frank (2007), 0706.2225.
 - [18] NASA, *The sunspot cycle*, <http://solarscience.msfc.nasa.gov/SunspotCycle.shtml>.
 - [19] D. Smart and M. Shea (1985).
 - [20] P. Grieder (2001).
 - [21] M. Ambrosio et al. (MACRO Collaboration), Astropart.Phys. **7**, 109 (1997).
 - [22] IGRA, *Monthly-averaged atmospheric temperature data: Pratica di Mare station*, <http://www.ncdc.noaa.gov/oa/climate/igra/index.php>.
 - [23] M. Aglietta et al. (LVD Collaborations), Astropart.Phys. **3**, 311 (1995).

Acknowledgments

Many thanks to Marco Cirelli, Olga Mena, Carlos Pena-Garay, Josef Pradler, Pasquale Serpico, Michel Sorel and Michael Trott for helpful conversations; and also to Adobe, for their indispensable graphics design and editing software.